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The applicability of photonic band gap structures in high Q resonators has been studied. A review of numerical simulations, experiments, and system design studies are presented. These results confirmed the technical feasibility of utilizing 2-D photonic band gap structures with high temperature superconducting end plates as high Q resonators for fabricating low phase noise oscillators. A particularly important result of the numerical simulations is that inverse structures (dielectric host with air holes) exhibited useful photonic band gap properties. Experiments performed at 10 GHz demonstrated two methods of modulating the defect mode frequency. A supplier of high temperature superconducting films, suitable for millimeter-wave photonic band gap resonators has agreed to collaborate with Tristan Technologies in a Phase II effort. Potential commercial and government applications for photonic band gap resonators with high temperature superconducting end plates have been identified.

Tristan Technologies has proposed to design, develop, and test a series of photonic band gap based oscillators with high temperature superconducting end plates, with the goal of commercializing a line of low phase noise ultrastable sources for the frequency range from 8 to 100 GHz.


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# Phase I Final Report

## Introduction

In the Phase I proposal we identified the need for low phase noise microwave oscillators which would overcome the limitations in present state-of-the-art devices. We suggested that a new class of very high Q resonators, based on the concept of a defect state in a Photonic Band Gap (PBG) structure between two High $T_C$ ($HT_C$) superconducting wafer endplates, could be used to develop a superior device. The experimental and theoretical results obtained during Phase I have further confirmed this. We expect to proceed to design, develop, and test a series of PBG based oscillators, with the hope of commercializing a line of low phase-noise, ultra stable sources for the frequency range from 8 to 100 GHz.

In Section I, we reproduce the six Specific Technical Objectives from Section D of the original Phase I proposal and we present a brief summary of our results for each objective. In Section II, we provide a more detailed discussion of our work toward these objectives. In Section III, we describe additional relevant results that we have obtained, and which further convince us of the practicality of utilizing PBG structures in commercial microwave devices.

## I. Specific Technical Objectives of Phase I and Summary of Results

*(1) – Engage in discussions with technical representatives of federal agencies, federal laboratories, and businesses to fully identify their problems in relation to the solutions obtainable by capitalizing on the unique advantages of PBG resonators.*

We have identified both commercial and governmental market needs for improved ultra stable microwave sources. Novel, very-high-Q resonators based on Photonic Band Gap (PBG) structures with $HT_C$ superconducting endplates may well fulfill these needs.

*(2) – Complete the numerical simulations of PBG structures as a function of system parameters, for 2-D and extend our capabilities to 3-D.*

We have performed an extensive numerical simulation study of potential configurations for PBG structures. Using these simulations, we have identified the inverse structure consisting of a solid dielectric sheet with a periodic array of holes as a practical configuration. This is expected to provide the necessary dimensional stability for the PBG devices.

*(3) – Perform analysis of possible frequency modulation properties and evaluate several practical implementations including a proprietary approach which may be promising.*

We have made an experimental study of several modifications to the defect region which forms the PBG cavity resonator, and have shown that it is possible to readily adjust the resonance mode as needed.

*(4) – Produce a plan for the construction of a cryogenic test facility suitable for complete experimental evaluation of potential PBG configurations.*

We have contacted many vendors of microwave components and have completed a design for a cryogenic based, mm wave test facility suitable for development of the devices to be evaluated in our proposed Phase II program.

*(5) – Collaborate with potential suppliers of $HT_C$ film material to evaluate performance as related to PBG structures.*

We interviewed several companies who are potential suppliers of $HT_C$ superconducting wafers suitable for high Q PBG resonators and who also have strong interests in microwave technology. As a result, we have formed a collaborative effort with Conductus Inc. Conductus has participated in the preparation of our Phase II proposal and will be a key team member if this work is funded.

*(6) -- Complete a report based on our study of the potential performance and applicability of PBG resonant structures for mono-frequency narrow band filters, high speed phase locked loops, and ultra stable low phase noise frequency sources.*

We have concluded that cryogenic PBG resonators, properly incorporated into microwave oscillators, are very favorable candidates for the next generation of commercial low phase noise frequency sources. A detailed program to accomplish this goal is presented in our Phase II proposal.

## II. Detailed Description of Phase I Results

In this section, we have organized the description of our Phase I work according to the Technical Objective addressed. In Section III, we discuss other work performed during Phase I which is outside the scope of these specific Technical Objectives.

**Technical Objective-1** -- *Engage in discussions with technical representatives of federal agencies, federal laboratories, and businesses to fully identify their problems in relation to the solutions obtainable by capitalizing on the unique advantages of PBG resonators.*

As a result of our discussions with researchers at various companies and government laboratories, we were able to identify a number of potential applications. These have been categorized as commercial and government applications and are described below.

### Commercial Applications

Communication

Low phase noise sources are desired for use as local oscillators in microwave communication links. This is especially true for systems employing direct-sequence spread-spectrum modulation (i.e., code division multiplexing). Low-loss, sharp-skirted filter banks are also desired for frequency-division multiplexing and power combining. Conductus has a close relationship with a small company, Endgate Technology, which is designing antenna systems for such satellite links - uplinks, downlinks, and crosslinks. Endgate has identified superconductive technology as being critical for at least the crosslink antenna feeds and views it as extremely beneficial for use in local oscillators and multiplexers.

Instrumentation

Many companies are working to produce very low phase-noise microwave frequency sources for a variety of instruments. An ultra stable master oscillator is needed to mix with incoming test signals for subsequent signal analysis. Several companies are pursuing strategies that include the use of superconductive technology for this application. Since many of the sophisticated microwave instruments already cost several tens of thousands of dollars, a 10 dB reduction in the low-frequency phase-noise floor would readily justify an added cost of $10,000.

## Government Applications

### Doppler Radar

We are aware of substantial needs within the DOD for improved Doppler radar. The challenge is to be able to find small moving targets (e.g., surface-skimming missiles) surrounded by stationary clutter. The phase-noise of existing sources spreads out the clutter signal in Doppler offset (i.e., velocity space) so that the target is hidden. Specifications already issued for Navy shipboard radar require oscillator performance which is better than that of the best, most recently developed technology; the all-quartz UHF surface-acoustic-wave devices produced by Raytheon. This continuing need for improvement in phase noise at frequencies close to the carrier constitutes a very significant near-term application for superconductive PBG resonator technology.

### Spread-Spectrum Communication

The Defense Department was the first user of spread-spectrum modulation, taking advantage of its features of covertness and immunity to jamming. These modulation techniques are just now entering the commercial market, where they offer advantages in spectrum utilization. Several companies are investigating and implementing products for cellular communication and other applications.

A major drawback of spread spectrum modulation, however, is the time required to resynchronize the transmitter and receiver. A low phase-noise oscillator can help by greatly reducing the correlation search volume for re-establishment of a link. The DOD's needs for this technology might serve to aid the insertion of these devices into future commercial systems.

### Electronic Warfare

Multichannel filter banks are very useful for signal sorting or presorting. These type of operations are widely used in signal-analysis equipment which gathers intelligence, issues warning of radar threat, or generates electronic countermeasures. The field is simply too new to be able to project the role that might be played by PBG structures. For example, we can mention that we have been able to place several discrete frequencies within the same band gap in one device, and also can expect to design a single configuration that has several bandgaps, each with its own defect resonance. In addition to the filter bank concept, ultra stable oscillators are also useful for implementing devices used for countermeasures.

**Technical Objective-2** – *Complete the numerical simulations of PBG structures as a function of system parameters, for 2-D and extend our capabilities to 3-D.*

Technical Objective 2 recognized that numerical simulation has to play a key role in our plan to develop a new state-of-the-art low phase-noise oscillator. It is important to appreciate that in contrast to metal walled, or single dielectric based resonators, one cannot simply calculate the resonant frequencies and associated eigenfunctions for PBG structures. Therefore, a major part of the Phase I effort was to establish the software and numerical methods needed for calculating the properties of a PBG structure as a function of geometrical and material parameters.

We developed an analysis technique and associated software to permit numerical simulation of the band structure for a lattice of dielectric scatterers in various configurations. Some of these configurations are illustrated in Fig. 1. Note that the dark shading represents the dielectric, the white represents air. Thus, we consider for example, a Square Lattice with Cylindrical Dielectric (SLCD) scatterers, and the inverse structure, SLCH, which consists of a square array of holes drilled in an otherwise uniform sheet of dielectric. We shall see that the "inverse" class of configurations is most important.

An illustrative example, the calculated bandstructure of a SLCD lattice with dielectric constant 9 and a filling factor a/d=0.38 is presented in Fig.2. (Note, the filling factor is the ratio of the scatterer radius, either cylinder or hole, to the lattice constant). Prior to the development of this software, the effort to obtain bandstructures was prohibitive for the type of systematic study needed. For each of the figures to follow, many hundreds of such of bandstructures were calculated and the resulting gaps analyzed automatically.

The most important feature of these data for the present discussion is the ratio of the width of the bandgap to the center frequency, df/f. In Fig. 3, we present df/f for the lowest band gap of a SLCD array as a function of dielectric constant and a/d. Note that large values of df/f are readily obtained. In Fig. 4, we present similar data for a triangular lattice with cylindrical dielectrics, (i.e. TLCD).

The ability to handle any shaped scatterer (dielectric or hole) may turn out to be very important. For example, sapphire has hexagonal symmetry about the C axis. It may be possible to grow a boule of sapphire with a periodic array of hexagonal holes or even columns. Thus, we specifically modeled hexagonal geometries, an example of the bandstructure for such hexagonal columns (TLHD) is presented in Fig. 5.

The reason the inverse structures (solid dielectric with air holes) are so important is dimensional stability. As an example of such an inverse structure, in Fig. 6 we present a SLCH for which there is a df/f of 0.1 at a dielectric constant of 9, and a corresponding a/d of ~0.46. A TLCH (triangular lattice with cylindrical holes) is presented in Fig. 7. Note that with a dielectric constant of 9, this configuration also has a quite satisfactory df/f at a/d of ~0.47. In Fig. 8 we present a SLHH for which we see that at dielectric constant 9 and a/d of 0.5 there is also a gap width of 0.1. The lattice structure "square lattice with hexagonal holes" is the simplest lattice that one can envision growing directly in Sapphire.

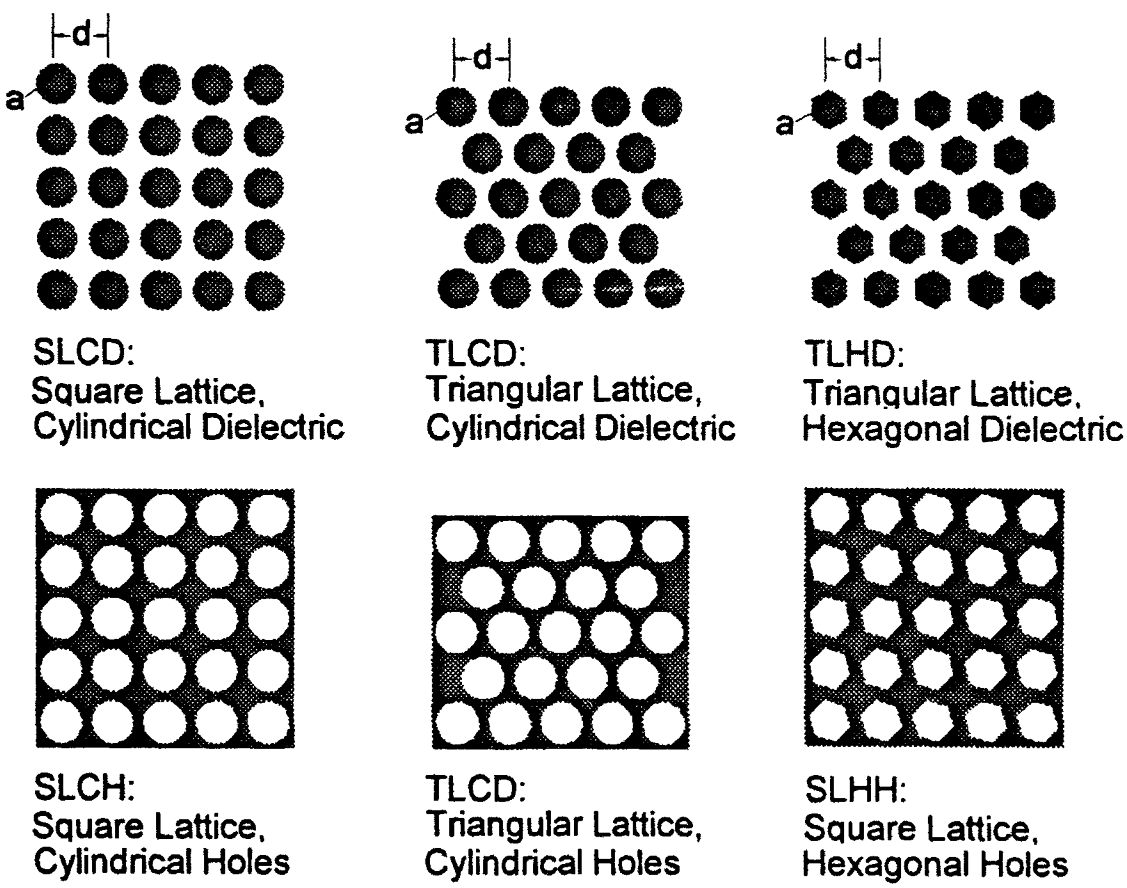


*Figure 1. Top view of various lattice types and scatterers used.*

**Technical Objective-3** – *Perform analysis of possible frequency modulation properties and evaluate several practical implementations including a proprietary approach which may be promising.*

To accomplish the third technical objective, we performed experimental modeling rather than numerical simulations. In Fig. 9 we illustrate how the defect modes develop as the radius of a single dielectric cylinder is reduced. The key point of this class of experiments is that the removal or addition of a local dielectric probe, perhaps mounted on a piezoelectric drive, can be

readily used to effect dynamic tuning and AFC. (NOTE: when the cylinder is totally removed, the defect mode illustrated is located in the second gap, and the corresponding electric energy density is that presented in Fig. 5 of our Phase I proposal).

An alternate procedure for tuning the frequency of a defect mode is illustrated in Fig. 10. Here the defect is a fully withdrawn cylinder, and the four nearest neighbors are systematically displaced towards or away from that defect lattice site. As can be seen, large tuning shifts of the defect mode are readily available.

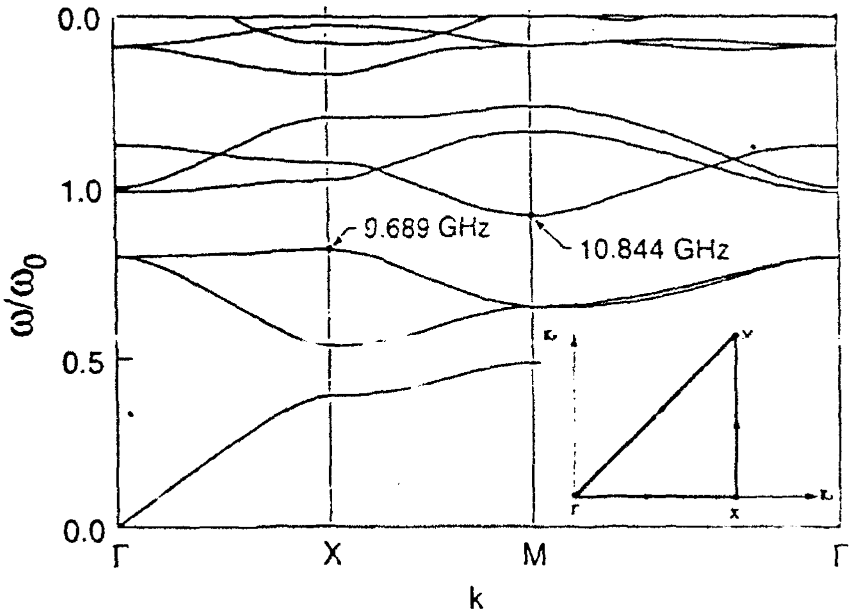


*Fig.2. The calculated 2-D band structure for a set of cylinders of radius a = 0.48 cm placed in a square lattice with lattice constant, d = 1.27 cm. The cylinders have dielectric constant e = 9. Note the photonic band gap between 9.689 and 10.844 GHz which corresponds to stop bands shown in Fig. 2(a) - (c). $\omega_0$ = c/pd*

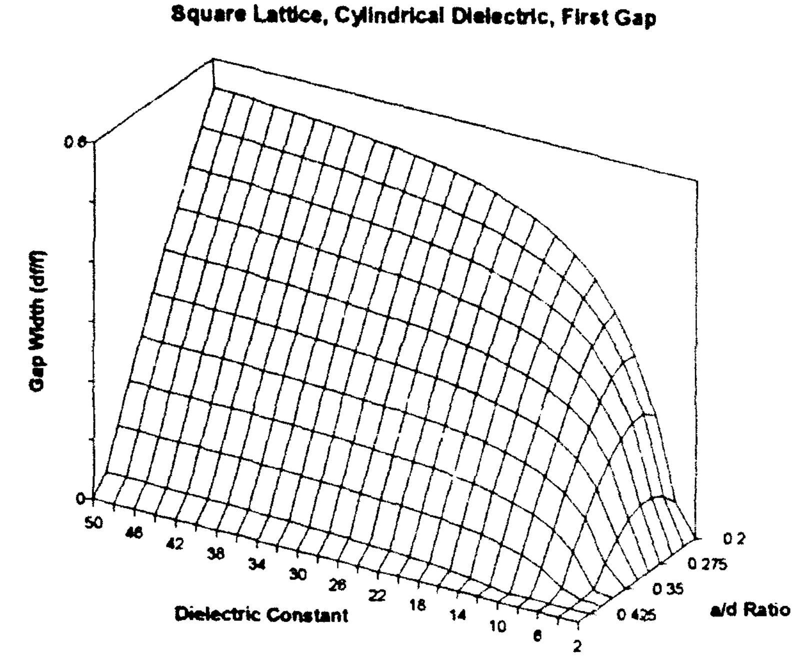


*Figure 3. Surface plot of band gap width as a function of dielectric constant and filling factor for SLCD.*

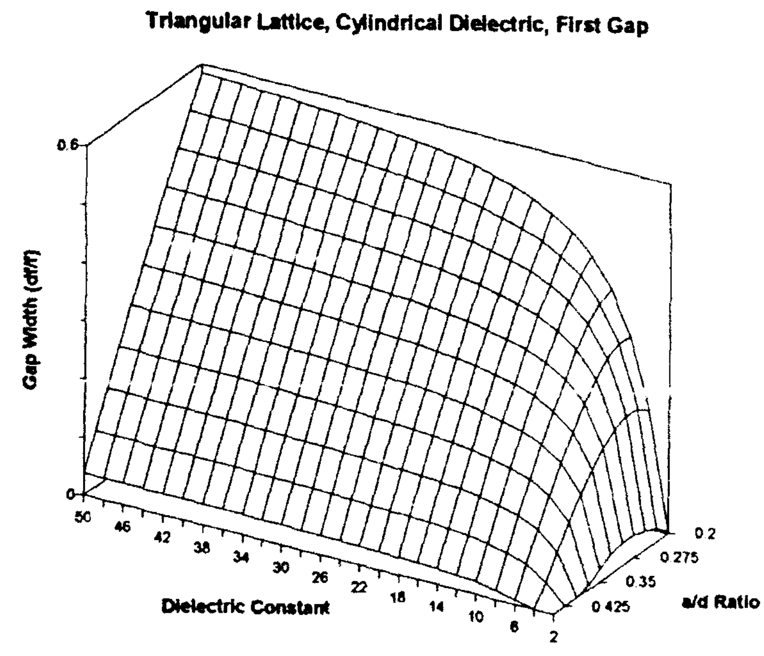


*Figure 4. Surface plot of band gap width as a function of dielectric constant and filling factor for TLCD.*

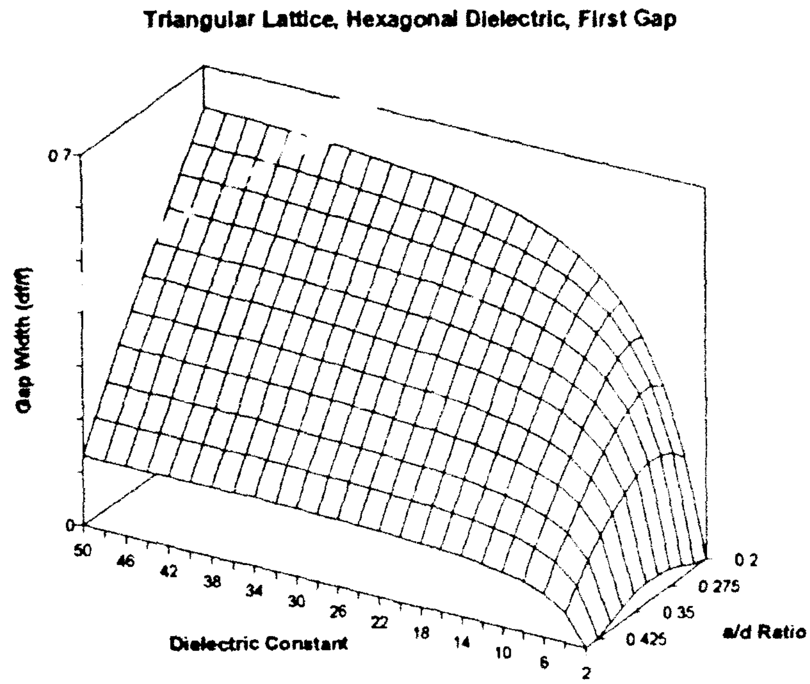


*Figure 5. Surface plot of band gap width as a function of dielectric constant and filling factor for TLHD.*

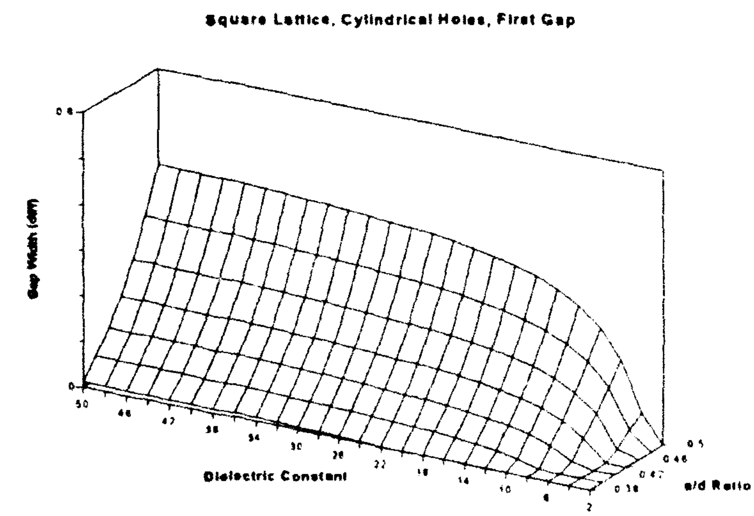


*Figure 6. Surface plot of band gap width as a function of dielectric constant and filling factor for SLCH.*

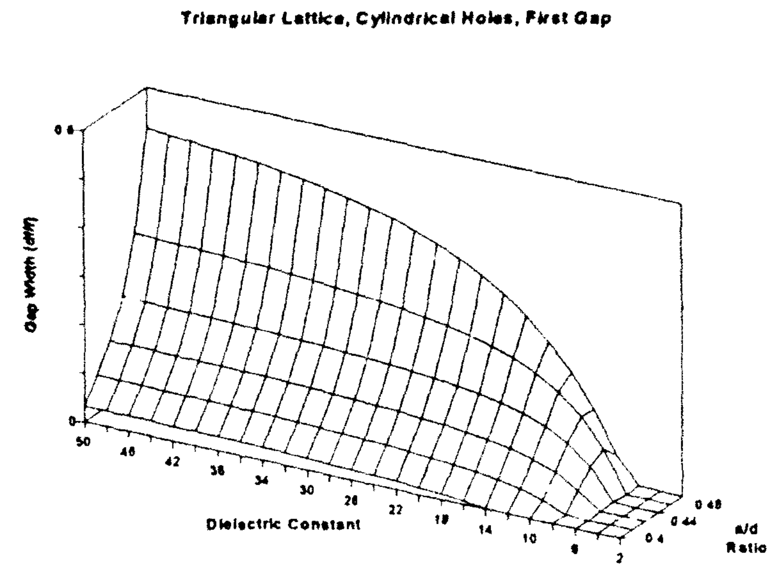


*Figure 7. Surface plot of band gap width as a function of dielectric constant and filling factor for TLCH.*

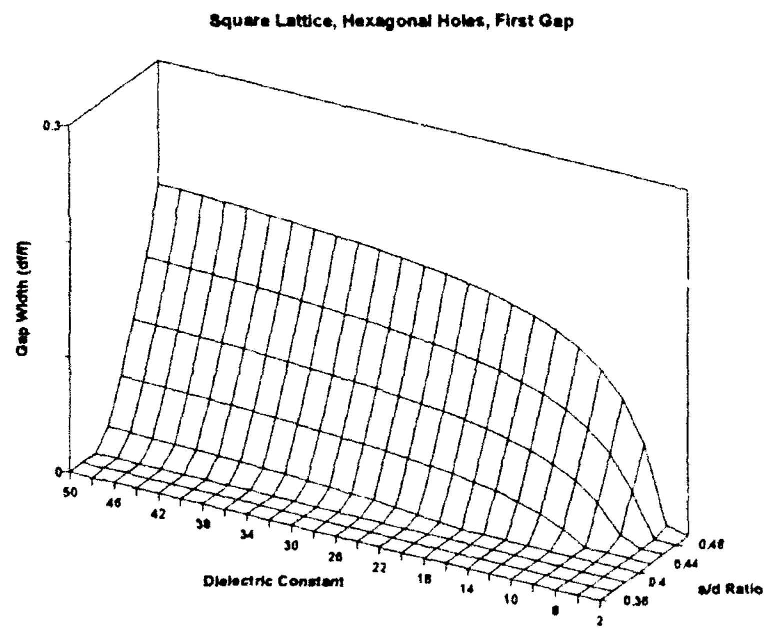


*Figure 8. Surface plot of band gap width as a function of dielectric constant and filling factor for SLHH.*

Frequency Modulation by Varing the Defect Diameter

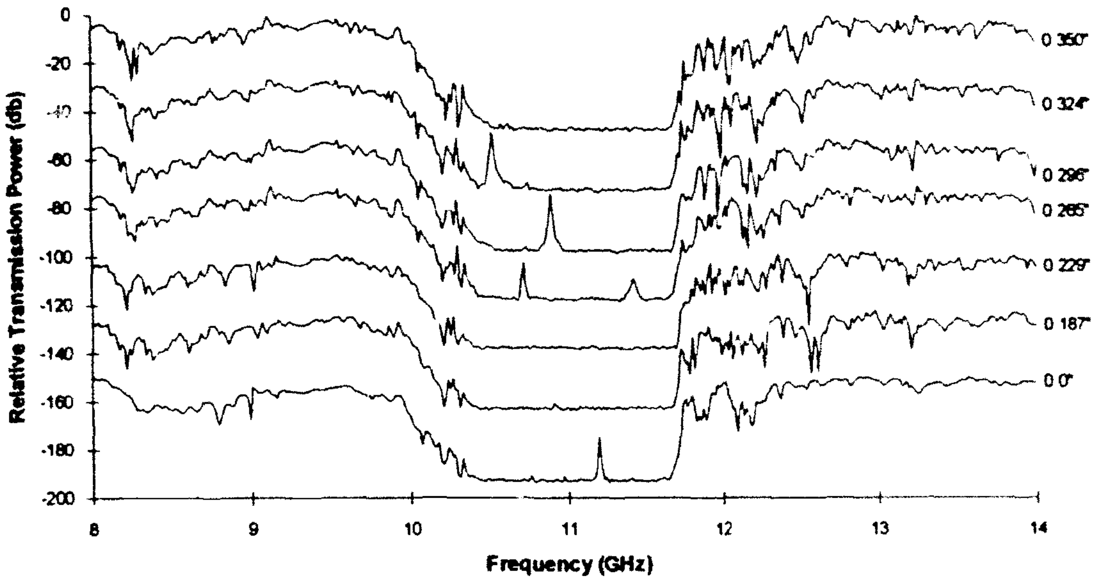


*Figure 9. Evolution of the defect mode as the diameter of the defect is changed. The defect diameter (in inches) is noted.*

**Technical Objective-4** – *Produce a plan for the construction of a cryogenic test facility suitable for complete experimental evaluation of potential PBG configurations.*

A schematic diagram illustrating our design for the cryogenic test facility to be constructed is presented in Figure 11. Note that this facility not only includes the cryogenic dewars etc. but also the automated movable microwave test probe facility which can be used to efficiently obtain the type of spatial mapping data presented in Fig. 3 of the original proposal. This type of data is necessary to confirm numerical simulations, and to fully evaluate the prototype systems to be constructed. This may also be very helpful in determining the optimum location of the input/output coupling ports that will be required.

We will use our modeling techniques to determine the maximum size and interior volume of the test chamber that is needed. From this, we will make the detailed drawings of the support fixtures, dewars, etc. The temperature control and other test data will all be under the logic supervision of a PC with a suitable special data logging program. The data logging program used will be a program that Tristan has already developed for in house systems with similar requirements.

Tristan has many man-years of experience in the design and fabrication of reliable cryogenic test systems. Once the system has been built and tested, it will be shipped to Conductus where the important phase-noise tests will be performed.

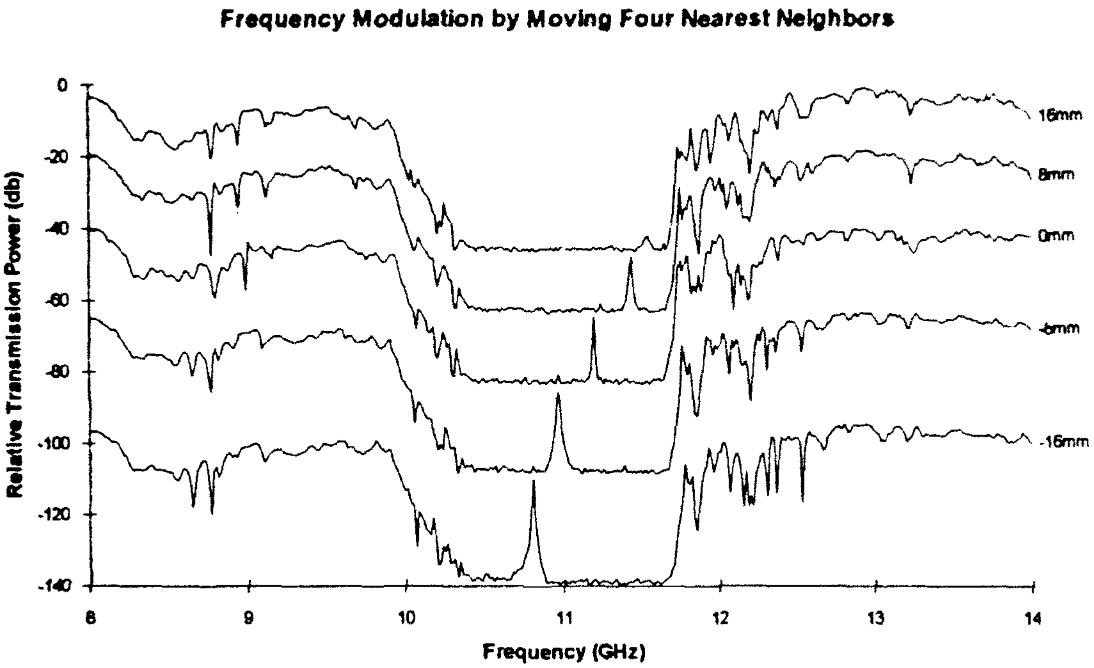


*Figure 10. Evolution of the defect mode as the four nearest neighbor lattice sites are displaced towards (negative displacement) and away (positive displacement) from the defect site.*

**Technical Objective-5** -- *Collaborate with potential suppliers of $HT_C$ film material to evaluate performance as related to PBG structures.*

We made presentations, and had detailed discussions, with three leading companies who have major interests in fabricating microwave quality $HT_C$ wafers and developing microwave products. We eventually selected Conductus Inc. as the best choice and we are pleased that they have agreed to participate as both a subcontractor and a collaborator. The role to be performed by Conductus is discussed in detail in our Phase II proposal.

**Technical Objective-6** -- *Complete a report based on our study of the potential performance and applicability of PBG resonant structures for monofrequency narrow band filters, high speed phase locked loops, and ultra-stable low phase noise frequency sources.*

The fulfillment of the sixth technical objective is met both by submission of this report, and in an even more important way, by the submission of the accompanying detailed Phase II proposal.

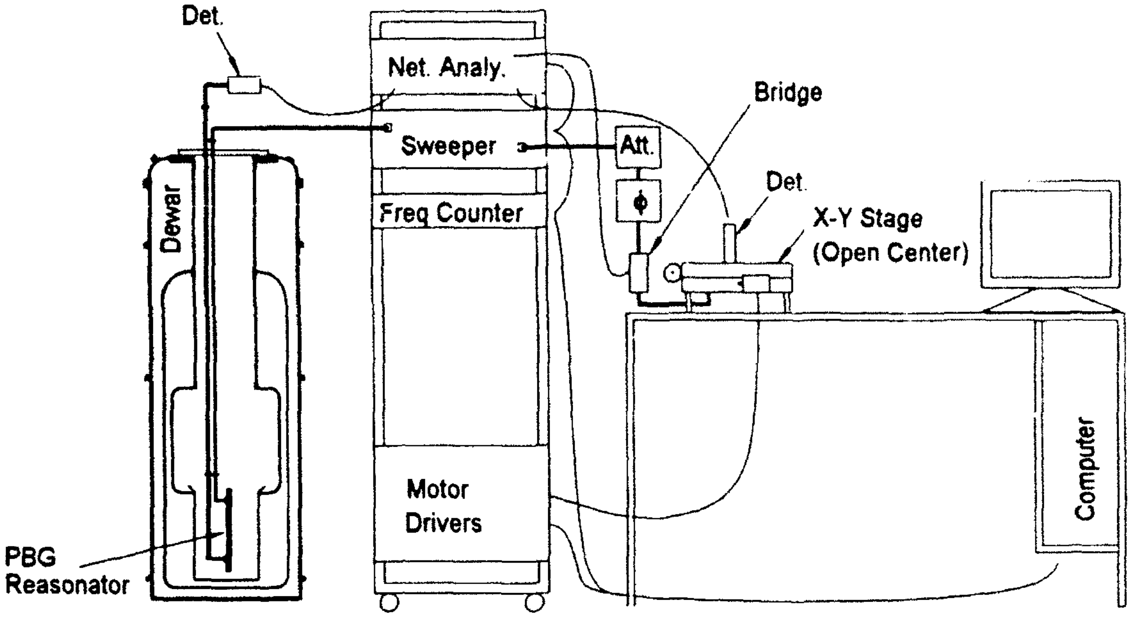


*Figure 11. Sketch of proposed millimeter-wave room temperature and cryogenic test setup. The millimeter-wave equipment will be shared between the two test sites. The room temperature site will be utilized to optimize defect mode and device coupling. The cryogenic setup will be utilized to measure dielectric losses and resonator Q.*

## III Additional Results

In addition to fulfillment of the specific technical objectives outlined in the Phase I proposal, we made important progress towards the design of a realizable PBG resonator product. As our numerical simulations revealed, the practicality of an inverse structure (solid dielectric and air holes), we investigated the possibilities for sources of pure sapphire, and modes of possible manufacture that might put in the holes. This is most important as we need to accurately place many hundreds of holes in the host dielectric sheet. We have found a vendor that can grow pure sapphire single crystals around a periodic set of molybdenum posts arranged in the form desired! We have every reason to expect that this process will also result in material of sufficient purity to maintain the very high resonator Q values we are seeking.

We have mentioned that we believe there are other commercial product opportunities utilizing PBG concepts. As part of our continuing desire to find such applications we will continue to participate in conferences, workshops, and other related activities to share information and gain insights into this

new subject. We are aware of the activities that are ongoing in the community that is interested in optical applications which are mainly concerned with 3-D, PBG structures. We believe that there may well be

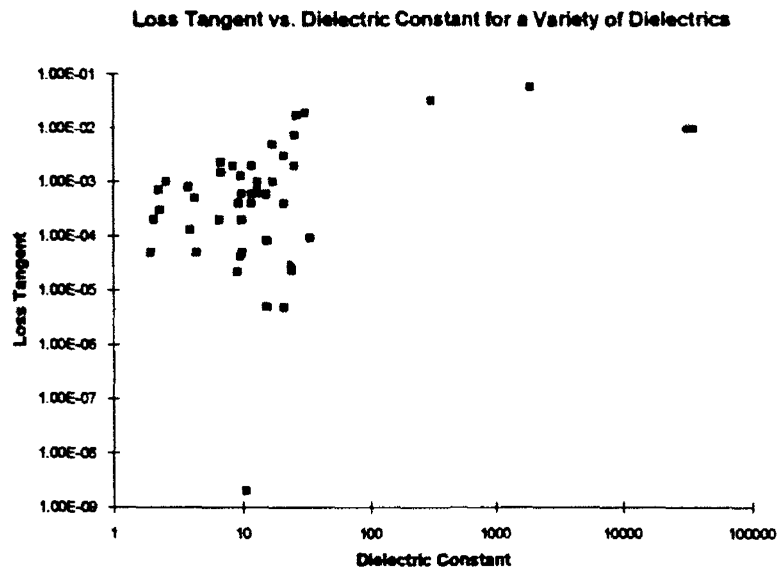


*Figure 12. Scatter plot for a variety of dielectrics, showing the trade off between dielectric constant and loss tangent. The lowest point is high purity sapphire, at cryogenic temperatures.*

related opportunities up to sub-mm wavelengths in 2-D and 3-D which we could eventually address. Towards this end, we made a general review of the properties of dielectrics that might be useful in PBG devices. We investigated dielectrics suitable at sub-mm wavelengths (i.e. Si and GaAs) as well as materials with very high dielectric constant which, due to device size reduction, may be useful in constructing devices around 1 GHz. These data are illustrated in Fig. 12.

Space prohibits a more complete discussion of all the design analyses and discussions with vendors performed during the Phase I program. Many manufacturers were contacted for performance, prices etc. of their test instruments and microwave components. We are confident that the experiences gained during Phase I have placed us in the proper position to accomplish the Phase II objectives which rely on this background work.